Survey on haptic rendering of data sets: Exploration of scalar and vector fields

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Abstract

Complementary to automatic extraction processes, Virtual Reality technologies provide an adequate framework to integrate human perception in the exploration of large data sets. In such multisensory system, thanks to intuitive interactions, a user can take advantage of all his perceptual abilities in the exploration task. In this context the haptic perception, coupled to visual rendering, has been investigated for the last two decades, with significant achievements. In this paper, we present a survey related to exploitation of the haptic feedback in exploration of large data sets. For each haptic technique introduced, we describe its principles and its effectiveness.

Keywords: Haptic rendering, Virtual Reality, Data exploration, Scalar fields, Vector fields.

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1 Introduction

We are now facing ever increasing amounts of data produced by various scientific and industrial fields. In addition to automatic data processing, it is more than ever necessary and possible to involve humans into the data exploration process. This integration is indeed required because in some cases (when the goal is not well defined or necessitates knowledge that cannot be completely formalized), automatic extraction techniques are limited. In medical data segmentation, a field where a lot of automatic processing methods have been proposed, Vidholm and Agmund [VA04] note that the problem remains unsolved. On the other hand, human-centered techniques are useful for the extraction of meaningful patterns from very large and abstract data sets [Nes03]. VR systems provide uniquely suitable environments to exploit to their full extend the capabilities of humans for multisensory activities. In particular, haptic perception can be very useful when the user attempts to precisely locate a feature within a volume, or to understand the spatial arrangement of complex three-dimensional structures [AS96]. For example, Visual/Haptic systems seem to be suitable for the analysis of large data sets resulting from Computational Fluid Dynamic (CFD) simulations. First, physicists use a large-scale stereoscopic display, visualize all the data volume or a part of it through different computer graphics techniques (texture based, direct flow visualization, etc.) [PVH+03]. Thanks to their knowledge and background, they may infer a

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mental scheme about the structure of the flow. After that the haptic feedback is useful for the analysis of a specific point of interest in the observed phenomenon. While being constrained on a 2D plane, users can more rapidly and easily access a target point within the virtual scene [Cou94][WH00]. Figure 1 exhibits a user analyzing an unsteady flow through some 2D slices and streamlines in a VR immersive environment by the mean of such visual/haptic system.

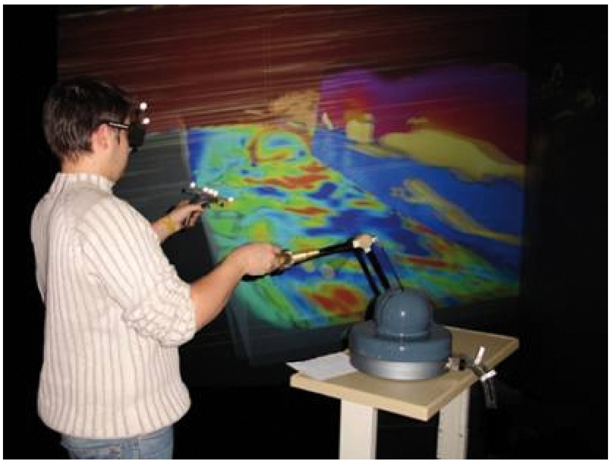

Figure 1: An accurate positioning of a colored cutting plane, in the CFD immersive application of the ANR "CoRSAIRe" project.

Works related to the use of haptic feedbacks to enhance the understanding of scientific data are usually classified according to the type of the rendering: surface and volume rendering methods. In surface rendering approaches, the haptic feedback simulates the response of touching a virtual surface, while volume rendering techniques directly convey the data presented at the probe position to the user by the mean of the haptic perception through a transfer function [LGY05]. However, we note that some approaches can be classified in both categories. This is indeed the case of the method presented in Avila et al. [AS96] which can be used for both surface and volume rendering. In order to provide an accurate classification in our survey, we divided the methods into two mains groups related on the nature of the analyzed data, namely scalar and vector fields. For more on taxonomies in standard scientific visualization, one can refer to [TM04].

This paper addresses a survey related to haptic rendering techniques used in the exploration of large data sets. Section 2 is devoted to scalar field rendering while section 3 describes the haptic exploration of vector field. Section 4 concludes the paper

2 Haptic rendering of scalar fields

This section discusses works related to the use of haptic cues for the display of single valued functions of three space variables. In this group of methods we denote two main categories. The first one concerns the rendering via a transfer function while the second one adresses surface rendering.

2.1 Scalar field through a transfer function

As mentioned in [LGY05] a transfer function makes it possible to convey information via a haptic feedback. Noma and Iwata [NI93, IN93] released one of the first work related to the exploitation of the haptic modality for multi-dimensional data exploration. Three transfer functions are proposed for the analysis of scalar field:

$$\overrightarrow{F} = \phi.\overrightarrow{V} \tag{1}$$

$$\overrightarrow{F_y} = \alpha.\phi \tag{2}$$

$$\overrightarrow{F} = \overrightarrow{grad\phi}.\overrightarrow{V} \tag{3}$$

We review below the main haptic rendering approaches based on transfer functions.

Viscosity Field: The value of the field (ϕ) is mapped onto the velocity of the haptic device $\left(\overrightarrow{V}\right)$ [NI93, IN93] (Equation 1). While moving in the data volume the user perceives a viscosity feedback proportional to the field value at the probe position. Hence, regions where data values are bigger feel more viscous to the user. Pao et al. explored this method in [PL98] (Figure 2). Later evaluations of Aviles and Ranta [AR99] and van Reimersdahl et al. [vRBKB03] reveal that this metaphor is very useful for rapidly scanning a volume in order to identify interesting regions. The viscosity mapping is suitable to inform about the value distribution in the volume but is not relevant for the analysis of a specific point. Indeed, since the force feedback is directly proportional to the probe velocity, trying to analyze a specific point requires a low speed that would generate a negligeable force [AR99].

Pseudo-gravity: According to Equation 2, the value of the scalar field (ϕ) is rendered as a mass by a constant direction force $\overrightarrow{F_y}$ proportional (α) to the field value (ϕ). For a given point, the greater the value of the field is, the heavier the point wiil appear [NI93, PL98]. With this method the hand of the user is thus attracted by regions having high density (Figure

2). If the attraction force is too strong, or in case of having many regions containing high values, the user can get tired rapidly due to the unidirectional character of the transmitted force.

Gradient Viscosity: While traveling through a volume, the gradient $\left(\overrightarrow{grad.\phi}\right)$ is mapped onto a viscosity (Equation 3). Hence exploring a local isosurface produces a frictionless rendering [PL98]. Using this method a fast intuitive exploration of local isosurface structures is expectable (Figure 2). However, if the magnitude of the attractive force is too high, or in the case of high frequency data, unstable behavior can occur in the form of vibrations.

Topography: Values are rendered on a virtual surface using a height map associated to the field value [PL98]. One notes that this solution offers a clear differentiation between extreme values of the analyzed field (Figure 2).

Gravity Scalar: In [vRBKB03] van Reimersdahl et al. present the VISTA FlowLib framework for interactive visualization and exploration of unsteady flow by extending the methods of Pao [PL98] et al. Their gravity scalar method assigned a mass to a pre-computed distance field. With this method users are attracted or repulsed by specified value. Their experiments conclude that within a scalar field framework, the *Gravity Scalars* method is best suitable to identify a chosen value, while the *Viscosity Field* method is best to identify zones containing a range of values.

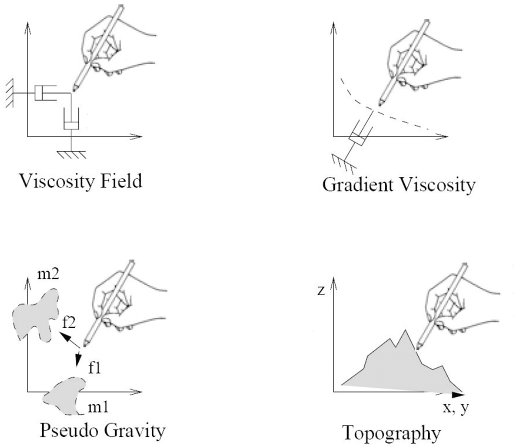

Figure 2: Methods of scalar field rendering in Pao et al. [PL98]

Point rendering: Fritz and Barner in [FB96] introduce a set of haptic rendering methods for the exploration of different types of data. Their framework implement a number of algorithms which depend on the dimensional type of the data and the expected representation. In case of 3D data, a point in space is rendered by computing its inclusion in a virtual sphere surrounding the probe position (Figure 3). Scalar fields are presented like a set of points which exert a stiffness force proportional to their distance to the probe. However, we note that in the presence of a lot of points, it may be difficult to infer their spatial distribution via this sole feedback.

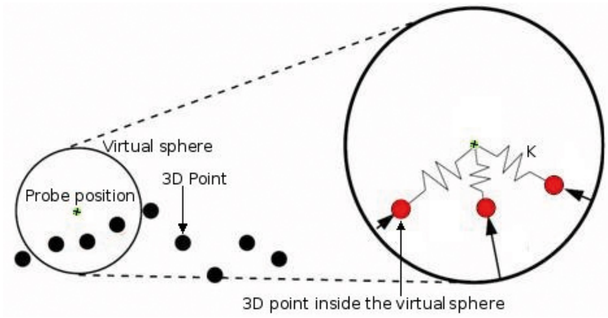

Figure 3: Haptic rendering of points. All the red points are rendered via a stiffness force (K) since they are inside the virtual sphere surrounding the probe position Fritz et al. [FB96]

Through this section we analyzed different methods where a transfer function is exploited in order to haptically convey the value of a scalar field to a user. Due to the diversity of information that these methods give access to, it is obvious to understand that none of them can be exploited for all situations. In each case the user has to select a properly suited technique. For this reason, we present table 1 which summarizes the reviewed approaches.

2.2 Surface rendering

In scalar field exploration, extracting an isosurface (locus of 3D points with a given value) can be very relevant in some applications. For example, in 3D medical imaging an isosurface may represent an internal organ or a bone. Moreover, one notes that a haptic segmentation system may speed up and facilitate the user interaction [SHS06]. During the last two decades, several haptic rendering methods have been developed for isosurface rendering. We define two categories: the methods using an intermediate representation and the direct rendering methods which are respectively discussed below.

Methods	**Advantages**	**Weaknesses**
Viscosity Field	rapid scanning of the volume	no point analysis
Pseudo Gravity	attraction to high values	get fatigue
Gradient viscosity	frictionless isosurface rendering	unstable behavior with high frequency data
Gravity Scalar	identification of choosen value	pre-computed time
Point rendering	point indentification via haptic feedback	a lot of points rendering

Table 1: Recapitulation of the explored approaches in rendering of scalar field via transfer functions

2.2.1 Surface rendering via an intermediate representation

Traditional approaches of surface rendering aim at extracting a polygonal approximation of isosurfaces from voxel data. Algorithms like the Marching Cubes (MC) [LC87] can be employed for the computation of the intermediate representation. Using this geometrical information the haptic feedback may be computed through a classic collision detection module coupled with a penalty based method [MRF+96, MS94]. As mentioned by many authors, using a surface based representation offers a stable feedback. However, due to the pre-computing time required by the surface estimation this method does not allow real time modification. To overcome this limitation, Galyean et al. [GH91] and later Körner et al. [KSW+99] have preferred a local computation of the MC algorithm. In this solution, the voxel data surrounding the probe position is used to compute the local surface in the environment of the probe. With this optimization, real time updating is possible since the surface is generated on the fly. However, there is a direct relationship between the computation time and the data count. This tends to restrict the application of such method to non massive data.

To overcome limitations related to the local exploitation of the MC algorithm, Adachi et al in [AKO95] propose another intermediate representation (Figure 4). In this approach a virtual plane is employed for controlling the haptic interface. In order to obtain a very fast haptic loop without dependence on the amount of data, the virtual plane is updated at a low frequency while maintaining a high update rate on the force control loop of the interface. Mark et al. [MRF+96] and Chen et al. [CHS00] have applied this approach to haptically render isosurfaces without any explicit surface extraction. In their algorithm, a virtual plane is used, to compute the pointwise interaction force applied to the haptic interface.

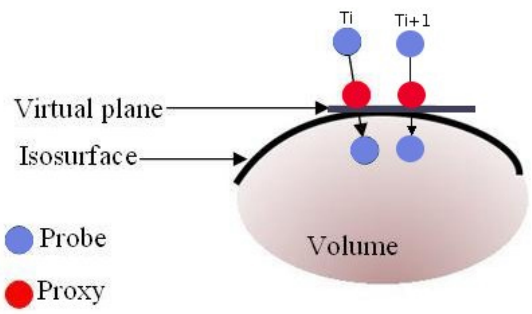

Figure 4: Exploitation of the intermediate representation

To mimic the touching of hard and soft contents when dealing with data sets resulting from Computed Tomography (CT), Lundin et al. in [LYG02] adapted the proxy method [RKK97] defined for the surface representation to the volumetric one. In the proposed approach the isosurface is locally approximated by a virtual surface defined by the local gradient at the proxy position. Hence, the proxy is not constrained by the geometrical representation of the isosurface but by the local gradient at the probe position. By controlling the motion of the proxy with several rules related to the nature (hard, soft) of the data surrounding its position, low density regions offer less resistance to the movement of the user. (The proxy is able to move more rapidly in such part of the data volume.) Thus, the haptic feedback produced with this method does not only render the presence of a virtual isosurface but also provide some relevant information related to the nature of this surface. Using this method a user can easily distinguish bones from skin or muscles. However, since the proxy is constrained by the local gradient, one has to note that within high gradient data, this virtual surface may not approximate the isosurfaces satisfactorily.

2.2.2 Direct Surface rendering

A well-known approach for direct rendering of isosurfaces was exhibited in 1996 by Avila and Sobierajski

[AS96]. Their work can address the haptic exploration of all the data volume or a part of it like an isosurface. For isosurface rendering this method does not require any intermediate representation of the surface. Indeed, the generated feedback $\overrightarrow{F}$ is expressed as a retarding and stiffness force directly approximated by the penetration distance to the virtual surface via a difference in the field value (Equation 4).

$$\overrightarrow{F} = \overrightarrow{S} + \overrightarrow{R} \tag{4}$$

In equation 4, $\overrightarrow{S}$ translates the stiffness of the environment while $\overrightarrow{R}$ expresses its viscosity ($\overrightarrow{V}$). Therefore $\overrightarrow{S}$ is oriented according to the volume gradient at the probe position ($\overrightarrow{N}$), while $\overrightarrow{R}$ tends to slow down the velocity of a user (Figure 5).

As mentioned by Avila et al. and Menelas et al. [MFAB08], this method works well with generic data volumes, offering a very fast haptic loop without using any surface representation. However, some unwanted vibrations can occur in regions exhibiting high frequency data. In such regions, due to the high gradient the difference in the field value is very strong hence does not approximate the penetration distance of the probe in the isosurface. These results have also been underlined by Fauvet et al. in [FAB07]. In fact, haptic vibrations occur in regions presenting tightening thickness of the isosurface. To solve this problem, Menelas et al. [MFAB08] have presented an improvement of this method in order to create a stable haptic rendering of isosurfaces in data sets containing high gradient data (Figure 6). Let us detail the approach below.

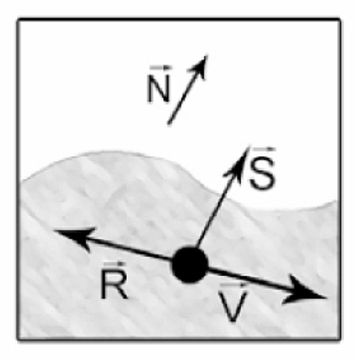

Figure 5: Representation of various components of the generated force

The method presented in [AS96] is combined with the proxy one [RKK97] through a 3D adaptation of the Bresenham algorithm. While exploring the data volume, a haptic feedback is rendered whenever the user hand crosses the isosurface from a greater value to a lower one. However, this force is null when the crossing is done in the opposite direction (from a lower to a greater value). The position of the proxy is then computed thanks to the gradient at the position of the crossing (Figure 6). This exploration does not require any intermediate geometrical representation, and so provides a fast haptic rendering loop. The results have been confirmed through psychophysical experiments aimed at following up an isosurface.

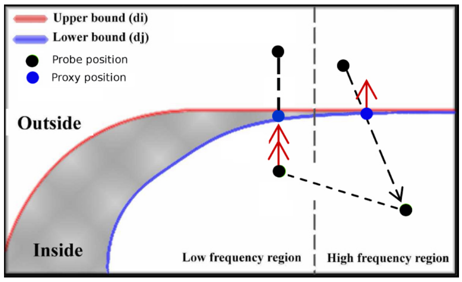

Figure 6: Computation of the proxy position in Menelas et al. [MFAB08]

Thereafter, a flexible method based on a more generic approach has been presented in [MAB08]. In this new solution, by launching rays in several directions Menelas et al. compute the position where the probe would be if it was constrained by a virtual isosurface (Figure 7). Once this position is computed this information is haptically conveyed to the user through the haptic channel by the mean of a penalty-based method.

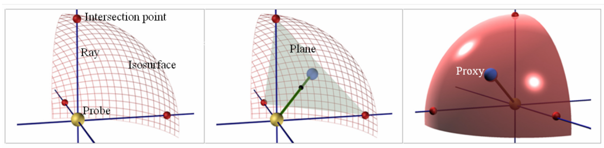

Figure 7: Computation of the proxy position in Ménélas et al. [MAB08]

In this section we reviewed the haptic rendering of isosurfaces in volumetric data. Conversely, to section 2.1, we can easily select the appropriate approach:

- Information provided by the technique of Lundin et al. [LYG02] is very useful for medical applications.

- In the case where an intermediate representation is expected, methods such as those of Mark et al.

[MRF+96] or Chen et al. [CHS00] are the best suited.

- The method proposed in [MAB08] offers best results for haptic rendering of isosurfaces based on a purely volumic approach (i.e. without any geometrical representation).

3 Vector field rendering

In this section we outline and discuss works related to the haptic perception of vector fields. In the same way as section 2.1, vectors are haptically conveyed to the user by the mean of a transfer function. We divide the vector field haptic rendering methods into three categories: guidance on streamlines, alignment on the field direction, conveying of local properties.

3.1 Guidance on streamlines

In this first group of methods, we distinguish five methods: the haptic-enhanced streamlines, the transverse damping, the relative drag, the directional constraint, and the navigation scheme.

Haptic enhanced streamlines: In order to enhance scientific visualization capabilities Durbeck et al. [DMW+98] integrate a haptic interface into a scientific visualization tool, thus allowing users to simultaneously see and feel a vector field. In the implemented system, the haptic methods render each vector as a force corresponding to the magnitude and the direction of this vector, while the graphic interface is presenting a subset of the vector field as streamlines or as arrow glyphs. In the exploration task the haptic feedback is analogous to the feeling produced when one puts his finger into a flow: vectors act upon his fingertip, dragging it in the same direction as the local flow field. If a user does not oppose the movement, his hand describes the trajectory of a fluid particule. More recently this method has been exploited in [LAC08] to display a wind (direction and magnitude) as well in [YBTS08] to guide users in following wind paths. The same approach has been used in [MAPB09] for the haptical analysis of an instant of an unsteady flow.

Relative drag: Lets the user perceive a feedback proportional to the difference between the field value vector and the velocity of the user [PL98] (Figure 8).

Transverse damping: This method aims to facilitate the following of a streamline. On one hand, a large viscosity is applied when gesture is transverse to the field direction. On the other hand in the field direction, a force proportional to field magnitude is exerted [PL98] (Figure 8).

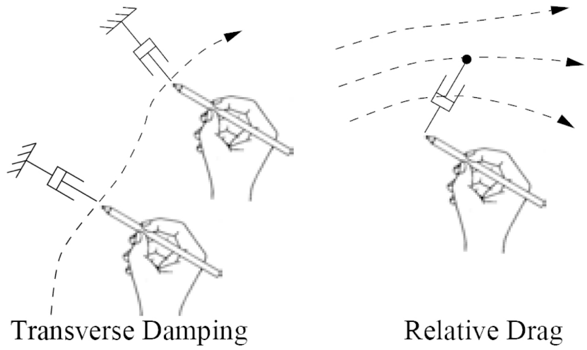

Figure 8: Transverse damping and Relative drag, Pao et al. [PL98]

Directional constraint: To take advantage of a directional constraint, Ikits et al. [IBHJ03] provide intuitive exploration modes for volumetric data sets. Their work offers a unified framework for different data modalities and effects such as texture and friction by the mean of several motion rules and transfer functions. Thus, to guide the user in a vector field, the proxy can be locked along a streamline.

Navigation scheme Since changing the dynamics of interactions can help targeting [BG00], Crossan et al. [CWMS04] have investigated the use of a haptic feedback to improve the navigation in a 3D space. The example of a gravitational field is presented. Consider a space where fixed targets are rendered as gravitational wells. In such conditions the force exerted on the hand of the user could provide great information about the distance and direction of nearby targets. In the same way Bartz et al. [BG00] also experimented a haptic navigation scheme. To ensure a fast and secure navigation in a critical environment two distance fields are computed. The first one reflects the distance between the probe position and the final destination, while the second one encodes the distance to a surface with which the user must avoid any contact. The second distance field can be seen as a potential field designed to facilitate the user tasks. Hence, the closer the user approaches the prohibited surface, the stronger a repulsive force will push him back along the gradient of this distance field. Experiments reveal that with appropriate parameters, the user was guided towards the target point, while staying clear of the surface.

3.2 Alignment on the field direction

The previous subsection surveys methods guiding the user's hand along streamlines. Now let us consider methods aim at the alignment on the field direction. Two methods were proposed.

Orientation Constraint: Informs on the orientation of the field by limiting the hand of the user according to the direction of the vector field (Figure 9) [PL98]. The hand of the user is thus forced to be aligned along the direction of the field.

Torque Nulling: Produces a torque proportional the field magnitude at the end effector position whenever this one is not aligned with the vector field (Figure 9) [PL98]. In such an approach the user is informed that his direction is not aligned to the one of the field but contrary to orientation constraint, he is not forced to be aligned.

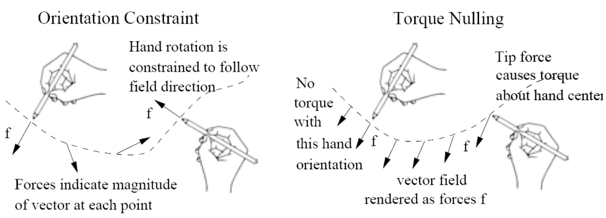

Figure 9: Orientation constrain and Torque Nulling, Pao et al [PL98]

In this category we note that the 6 DoF capabilities of the haptic device is exploited is order to provide information related to the orientation of the vector field. (This is not the case of most other proposed rendering schemes)

3.3 Conveying of local properties

This subsection reviews the methods where the haptic feedback are exploited to convey some local properties of a vector field. Five methods are presented.

Vortex Torque: Provides torques proportional to the local curl or vorticity of the field. It hence offers a natural rendering of some properties of a vector field that are hard to visualize [PL98]

$$\overrightarrow{F} = \overrightarrow{A} \times \overrightarrow{V} \tag{5}$$

Lorentz force: Let us denote: $\overrightarrow{A}$ the vector of a voxel volume, $\overrightarrow{F}$ the reaction force and $\overrightarrow{V}$ the velocity of the probe. In Noma et al. [NI93]the Lorentz force of a vector field are directly rendered by the mean of the Equation 5.

Shock detection: Motivated by problems related to shock structures and vortices visualization in data sets resulting from CFD applications, Lawrence et al [LLPN00] exploit the accuracy of the haptic channel for local properties to complement the visual perception of such structures. Thanks to the haptic feedback the user can be alerted on the presence of any secondary shock (even invisible) contained in the main one. This method allows free motion in regions having low gradients. Within the shock region, the forces applied to the user result in behavior similar to a ball on a hill. The shock surface can only be penetrated from the low density side ($\rho \leq \epsilon$) by pushing against the rendered force hence allowing users to easily understand regions representing high and low density without cluttering the visual display with additional data (Figure 10). For vortex visualization, they implemented two added capabilities: an exploratory and an identification mode. In the exploratory process the haptic device acts as a 3D mouse allowing users to explore local properties of graphically displayed streamlines. In the vortex core identification, a torque characterizing a vector that can be the vorticity, the acceleration or the jerk is rendered to the user. When the identification mode is activated in areas with vorticity the user is informed on the shape of the vortex core. In such model, any effort to move the haptic interface in a direction perpendicular to the current orientation of the field results in a strong opposing force.

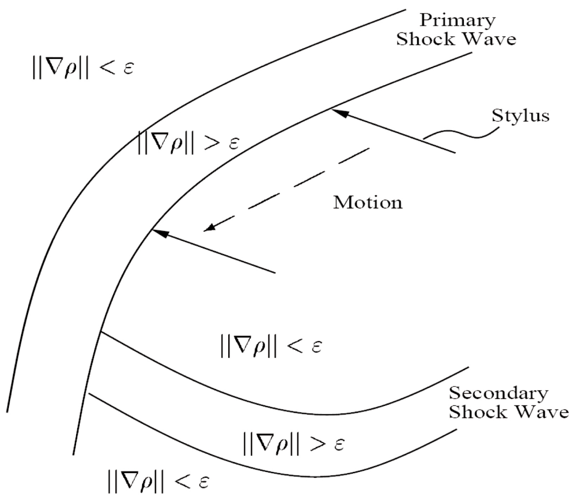

Figure 10: Haptic rendering of a secondary shock in Lawrence et al. [LLPN00]

Proxy based model: Following the surface rendering, Lundin et al. in [LYG02] extend their work to a general, proxy-based approach for volume exploration [LGY05]. Local properties of the volumetric data are simulated through a set of haptic primitives. Line primitive is using to convey the orientation of vector field, and a surface and friction mode for representing implicit and penetrable surfaces. In [LSCY05] they modify the proxy model in order to explore CFD data sets. The proxy is neither constrained by a surface [RKK97] nor by data features [LGY05]. However, whenever the probe moves in a direction perpendicular to the flow field, the user feels a viscosity feedback which informs him about the flow direction.

Vibration cues: In [LAC08] atmospheric turbulence is rendered via pseudorandom vibration. More recently, in [MAPB09] some vibration cues of a 6 DoF device are exploited in order to provide information about the local explored area. In this approach the vibration feedback aimed at reinforcing the visual rendering in order to facilitate the build of a mental map of the flow field.

Texture mapping: In [YBTS08] meteorological information such as cloud are presented haptically by the mean of texture mapping.

In this section we reviewed different methods which aim at the haptical exploration of a vector field. Unfortunately, as in the case of the haptical rendering of scalar field with transfer, we believe that each method brings specific advantages and must be used according to its intended. In order to help users in their choices, the table 2 summarizes the main features of each approach.

4 Conclusion

In this paper we presented a large overview on the haptic rendering methods used for the analysis of massive data sets. This survey was structured according type: scalar and vector fields. For scalar fields, we distinguished two main categories, surface rendering and rendering through transfer function. About surface rendering we note that different methods have contributed to the haptic perception of surfaces (via the *Intermediate* and the *Direct Surface Rendering*). Haptic rendering of isosurfaces was found to be suited to the rendering of physical properties (e.g. hardness of tissues in medical applications). Other haptic feedbacks are better fit to rapid inspection or localization of extrema. Furthermore, when exploring vector fields, haptics can provide guidance, inform about the orientation or convey local properties.

With this survey, we noted how specific are the proposed approaches in the haptic analysis of large data sets. For instance, most haptic interfaces offer only one point of interaction. Furthermore, only a few methods exploit the 6 DoF capabilities of haptic interfaces. We believe that no generic haptic rendering method can respond to the large variety of situations encountered in the exploration of large data sets. Instead, we advocate the design of a more complete library of haptic schemes to deal with more and more demanding applications. Other feedbacks such as textures, friction and vibrations remain unexplored in the haptic exploration domain. Finally, knowing that the haptic feedback is fairly localized, we think that the coupling with other sensory cues such as audio is a very promising area for large data sets exploration.

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Methods	**is suitable to**
Haptic enhanced streamlines	Reinforce the rendering of a streamline
Transverse damping	Facilitate the following up of a streamline
Relative drag	Perceive difference between the field value vector and his own velocity
Directional constraint	Provide intuitive exploration mode
Navigation scheme	Guide user in navigation
Orientation Constraint	Iinform on the orientation of the field
Torque Nulling	Inform on the orientation of the field
Lorentz force	Perceive Lorentz force of a magnetic field
Vortex Torque	Perceive vortex core
Shock detection	Detect second invisible schock
proxy based model	Convey focal properties of the volumetric data

Table 2: Recapitulation of the explored approaches in rendering of vector fields via transfer functions

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